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Review

Energy-Efficient and Smart Bicycle Lamps: A Comprehensive Review

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Abstract: In this review paper, information about bicycle lamp technical parameters is provided. The review is based on the searched Web of Science (WoS) and Scopus bibliographic databases and Transportation Research Information Services, which include references to books, technical reports, conference proceedings, and journal articles. This review showed that these papers about bicycle lighting legal rules in given countries are very easy to reach, but deep searching must be performed to find this research paper having the information about types of optical systems and light sources used in bicycle lamps. This research was conducted using PRISMA 2020 assumptions in the area of bicycle lighting technologies and innovations. The information about bicycle lamp technical parameters was obtained on the basis of the examination of technical documents and papers from high-impact journals. The author's review shows that contemporary bicycle lamps are becoming increasingly smarter and more energy efficient, while also enhancing safety and comfort for cyclists on their routes in and beyond urban environments.

Keywords: lamps; light sources; energy efficiency; smart lighting; legal rules

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Citation: Fryc, I.; Listowski, M.; Fan, J.; Czyżewski, D.. Energy-Efficient and Smart Bicycle Lamps: A Comprehensive Review. *Energies* **2024**, *17*, 5335. https://doi.org/10.3390/en17215335

Academic Editor: Francesco Nocera

Received: 3 October 2024
Revised: 19 October 2024
Accepted: 23 October 2024
Published: 26 October 2024

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1. Introduction

In order to reduce electricity consumption in cities and ensure an ecological lifestyle for residents, bicycles are becoming an alternative to passenger cars [1,2]. Environmentally-friendly cargo bicycles are also indicated as an alternative to cargo vehicles, which are especially appreciated for cargo delivery in cities with the numerous traffic restrictions and high population density [3]. It has been shown that cyclists are at increased risk of being involved in a traffic collision due to poor cyclist visibility [4]. Statistics show that using a bicycle after dark is associated with the possibility of serious injury and even death [5]. Although the intensity of cycling is much lower at night, the risk of a cyclist being involved in an accident increases by up to 55%, and the risk of a fatal accident is twice as high [6–8]. The scientific studies on bicycle lighting indicate the significant impact of its quality [9] on the number of accidents involving cyclists. Given these facts, it is important that bicycle lamps have a high-value shaped luminous flux. Therefore, the use of light sources with high luminous efficacy and the design of lighting fixture optics to ensure their energy efficiency are a necessity for modern bicycle lighting. In addition, by extending the functions of lighting fixtures, i.e., smart type fixtures, it is also possible to influence road safety [10–12], and energy efficiency [13] in cities aspiring to the title of "a smart city".

The concept of a "smart city" has gained significant recognition and social acceptance, thereby contributing to its current phase of rapid development [14,15]. The new urban development projects are currently being created, and the existing ones are being modernized. One of the fundamental elements of smart cities is the implementation of contemporary systems for the measurement, transmission, and analysis of data. This approach facilitates

the improvement of residents' quality of life and more efficient conduct of urban operations at various levels, including waste management, administration, transportation, electricity, and security. In a smart city, the double objective is to satisfy the needs of residents while simultaneously protecting the environment. Consequently, these cities are equipped with sophisticated systems for the optimal management of urban infrastructure. The intelligent traffic management system that facilitates dealing with the problem of traffic congestion in urban areas [12,16] is an illustrative example of such a system. An additional example of such a system is the road lighting systems that are capable of adapting to the fluctuations in traffic intensity and, in the absence of vehicles, reducing the luminous flux in order to conserve electricity [15,17].

The integration of bicycles into the concept of a smart city is a relatively recent phenomenon. Indeed, it was only recently that this type of transportation has become an integral component of the vision for smart city development on a global scale [18–20]. Nevertheless, the expectations and plans for bikes are considerable. As a consequence of the initiatives being undertaken to utilize bicycles equipped with smart lighting fixtures as active sensors capable of acquiring, processing, and transmitting data in real time [18–20]. The city's future can be managed by controlling traffic, identifying dangerous areas, and monitoring accidents. This will enhance the security of the road users. However, for bicycles to become a fundamental component of the smart city system, they must be equipped with intelligent lighting fixtures that facilitate communication. It is of the utmost importance to recognize that, in addition to the mentioned intelligent functionality, these lighting fixtures must comply with the legal requirements of the countries in which they will be utilized. Furthermore, it is essential to verify the sources used in order to obtain the accurate photometric [21–24], and colorimetric parameters [25].

2. Global Bicycle Lighting Legislation

The lack of global standards for technical parameters and lighting equipment on bicycles represents a significant area of regulatory divergence. The number and manner of mounting lamps as well as the requirements for light and technical parameters of position lamps and reflective elements vary according to the legislation and road traffic regulations of the respective country. The European Union (EU) and non-EU countries have different regulations concerning bicycle lighting. The EU has established bicycle lighting standards that are rooted in the 1968 Vienna Convention [26]. In the EU, bicycles are required to be equipped with the white or yellow light at the front [27] and the red light at the back (Figure 1).

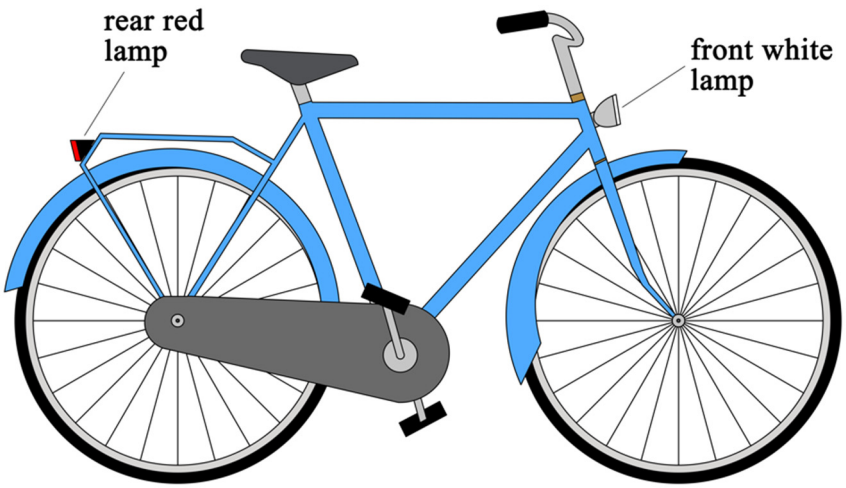


Figure 1. The required bicycle lighting according to the Vienna Convention [26].

At present, there are neither internationally recognized standards or regulations regarding the technical specifications of bicycle lamps and optical systems nor any require-

ments concerning the types of light sources and their energy consumption. A limited number of countries have introduced comprehensive guidelines that stipulate the technical specifications and requirements for bicycle lamps. In the Czech Republic, bicycle lighting is regulated by a series of requirements referring to the technical parameters of position and reflective lights (Table 1) [28]. The bicycle lighting requirements of individual EU countries are listed in Table 2, while those of non-EU countries are listed in Tables 3–5.

Table 1. Bicycle lighting requirements according to the regulations applying in the Czech Republic [28].

Active Lighting (Position Lights)	Reflective Elements
In conditions of limited visibility, the bicycle must be equipped with: (a) white lights shining towards the front of the vehicle, illuminating the ground at a distance of 20 m from the lamp. The lamp cannot change the set position automatically or through unintentional movement of the user; (b) red rear light, which may have a built-in reflector; red flashing lights are also permitted; If these types of lights are battery powered, the battery capacity must allow them to operate continuously for 1.5 h.	The reflective surface of the reflector must not be less than 2000 mm^2, and the shortest side of the quadrangle inscribed in this surface must be at least 40 mm. The reflector must be permanently attached to the left side of the bicycle or along the axis running through its center at a height of 250 mm to 900 mm above the road. The luminous surface must be perpendicular to the road on which the vehicle is traveling, with a possible deviation of $\pm 15^{\circ}$, and perpendicular to the axis running along the bicycle, with a possible deviation of $\pm 5^{\circ}$. Red and white reflectors may be replaced by reflective materials with similar properties. The rear reflector may be replaced by reflective materials placed on clothing or footwear.

Table 2. Regulations regarding bicycle position lights in selected EU countries.

Active Lights (Positioning Lights)						
Country	**Time to Use During the Day**	**Color (Front Light)**	**Color (Back Light)**	**Fixing/ Attched**	**Blinking Lights**	**Parameters**
Austria	whole day	white or yellow	red	to the bike	only on the back	on the front I_{min} = 100 cd, on the back I_{min} = 1 cd
Belgium	from dusk to dawn and for visibility below 200 m	white	red	to the bicycle, clothes, helmet	front and back allowed	the rear light at night must be visible from a distance of min. 100 m
Bulgaria	all vehicles are required by law to be equipped with "adequate" lighting					
Denmark	from dusk to dawn and with limited visibility during the day	white	red	to the bike	front and back allowed with f_{min} = 3.33 Hz	no glare lights visible from a distance of 300 m and
Finland	from dusk to dawn and with limited visibility during the day	white or yellow	red (back light is not mandatory)	to the bike on the height (0.30 ÷ 1.30) m under ground	is forbidden	no glare lights
France	at night and with limited visibility during the day	white or yellow	red	N/A	only permitted as an addition to the no blinking lamp	N/A
Ireland	whole day (may not light up when the bicycle is being operated or stopped)	white or yellow	red	to the bike	front and back allowed	the front of the bicycle is to be visible from the "appropriate distance", and the rear from a distance of 152.4 m
Italy	whole day	white	red	N/A	N/A	N/A
Latvia	at night and with limited visibility during the day	white	red	N/A	N/A	N/A
Lithuania	in the dark	white	red	N/A	N/A	N/A
Nederland	from dusk to dawn and in poor weather conditions during the day	white or yellow	red	to the bike or on clothes, back light on the height (0.26 ÷ 1.20) m above ground	forbidden	white visible to the front, red to the rear, without glare for other road users

Table 2. *Cont.*

Active Lights (Positioning Lights)						
Country	**Time to Use During the Day**	**Color (Front Light)**	**Color (Back Light)**	**Fixing/ Attched**	**Blinking Lights**	**Parameters**
Poland	from dusk to dawn and in the tunnels	white or yellow selektywna	red	at a height of (0.25 ÷ 1.50) m above the roadway	front and back allowed	both lights illuminated by traffic lights should be visible at night with min. 150 m
Romania	whole day	white	red	to the bike	N/A	N/A
Slovenia	whole day	white	red	to the bike	N/A	N/A
Sweden	whole day	white or yellow	red	to the bike	front and back allowed with f_{min} = 3.33 Hz	the luminous flux of the lamps allowing adequate visibility from a distance of 300 m

Table 3. Bicycle reflective lighting regulations in selected EU countries.

Country	**Reflective Element**			
	Front	**Back**	**On Wheels/Tires**	**On the Pedals**
Austria	the required reflective lighting in Austria does not apply to racing bikes			
	white	red	on each of the wheels, a yellow reflector with an area of min 20 cm^2 or tires have reflective rings	two yellow for each
Belgium	white	red (different in color from the positional one)	reflectors visible from the side required	required
Bulgaria	statement that reflectors are required			
Denmark	white	red	yellow reflector on each wheel or reflective rings on the tires	two yellow lights seen from behind
Finland	The following requirements for bicycles over 10 kg: Front and rear lights placed (300 ÷ 1200) mm above the road.			
	white	red	yellow reflector on each wheel	one yellow for each
France	white	red	orange on wheels	orange on each
Ireland	not required	red visible from a distance of 99 m	not required	not required
Italy	The obligation to have reflectors at the front and rear of the vehicle.			
Latvia	not required	not required	two orange reflectors on the wheels on both sides	not required
Lithuania	not required	red	orange reflectors visible on both sides	not required
Nederland	not required	red	white or yellow on wheels	four at orange color
Poland	not required	at least one red (other than triangle shape)	not required (wheel lights and tire rings allowed)	not required but allowed
Romania	required from dusk to dawn: When riding a bicycle, it is required to wear clothes with reflective elements.			
	white	red	not required	not required
Slovenia	white	red	yellow on both wheels	not required
Sweden	white	red	yellow or white when seen from the side	not required

Table 4. Bicycle position lighting regulations in selected non-EU countries.

Active Lights (Position Lights)						
Country	**When the Requirement Applies**	**Color Front**	**Color Back**	**Way Fastenings**	**Lights Flashing**	**The Value of the Luminous Flux or Information About the Perception of Lighting**
Bosnia and Herzegovina	from dusk to dawn and with limited visibility during the day	white	red	not stated	not stated	not stated
Iceland	in the dark and with limited visibility	white	red	not stated	not stated	not stated
Switzerland	whole day	white	red	to the bike	not stated	no glare effect for other road users
Ukraine	When riding at night and in conditions of limited visibility, the bicycle must have lights installed and turned on					

Table 5. Bicycle reflector regulations in selected non-EU countries.

Country	**Reflective Element**			
	Front	**Back**	**On Wheels/Tires**	**On the Pedals**
Bosnia and Herzegovina	not required	red	not required	one yellow or one orange
Iceland	white	red	yellow or white mounted on spokes	yellow or white on each
Switzerland	white	red	not required	with a surface area of at least 5 cm^2 (not required on bikes with clipless pedals)
	with a size of min. 10 cm^2, visible from min. 100 m			
Ukraine	white	red	orange visible from the side	not required

It should be noted that the more extensive regulations (StVZO §67, Table 6) regarding bicycle lighting are applied only in Germany (Figure 2) [29]. The regulations stipulate that all lamps utilized in vehicles in Germany must be designed to prevent glare for other road users. This is achieved by ensuring that the optical systems of these lamps effectively limit the luminous flux emitted in the specific angular ranges. Additionally, according to the same standard, the rear lamp of a bicycle must be located no lower than 250 mm above the road surface.

Table 6. Requirements for bicycle lighting presented in the StVZO§67 standard [29].

Active Lighting (Position Lights)	**Reflective Elements**
The bike must be equipped with the front and rear lights powered by a 6V/3W dynamo. Racing bikes under 11 kg are exempt from this requirement if they use battery-powered lights. Mounted securely, a white front light is required. Its operation must be permanently ensured, and it cannot be covered with dirt.	Requirements: one white reflector at the front, two yellow or white reflectors placed on the spokes or reflective strips on the sides of the tires, two yellow reflectors placed on the pedals, and one red light at the rear of the bicycle, placed no higher than 600 mm from the road surface.

In Great Britain, there are also detailed guidelines (Table 7) for lighting for two-wheelers. The regulations require that each device must meet the standard BS 6102 [30] or its equivalent. This standard states that it is possible to fit additional lights that do not have to meet the requirements of the standard apart from those concerning the color of the light, the frequency of flashing, and the possibility of dazzling other road users.

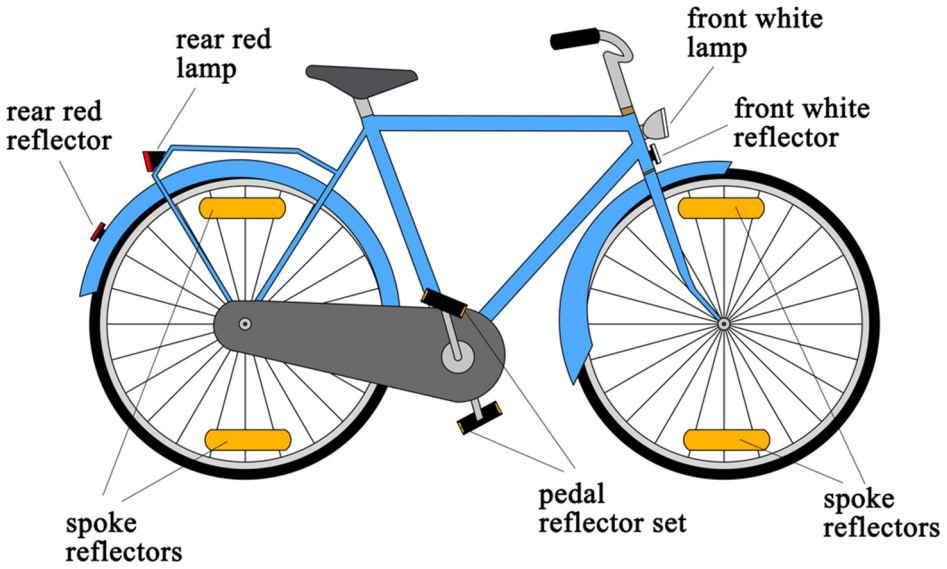


Figure 2. Required bicycle lighting according to the StVZO§67 [29].

Table 7. Requirements for bicycle lighting presented in the BS 6102 standard [30].

Active Lighting (Position Lights)	Reflective Elements
The obligation to have lighting applies to cyclists traveling on the roads from dusk to dawn. The front white light should be placed in the middle of the vehicle or on the edge and should be lower than 1500 mm above the road surface. The rear red light should also be placed in the middle or on the edge of the bicycle at a height of 350 mm to 1500 mm above the road surface and shine to the rear. Flashing lights with a frequency of 1 Hz to 4 Hz and a luminous intensity of more than 4 cd are permitted.	The bicycle must be equipped with a red reflector at the rear of the bicycle and four yellow lights on the pedals. The red reflector must be placed in the middle or at the edge of the bicycle at a height of 250 mm to 900 mm above the road surface and direct the reflected light beam towards the rear. It is permitted to use lights that meet standards corresponding to BS 6102. The only currently applicable standard that meets this criterion is StVZO§67.

Despite the comprehensive nature of these requirements, as evidenced in the article "Lighting for Cycling in the UK: A Review" [31], it remains unclear whether the current standards for lighting bicycles and cyclists are optimal or even sufficient for their intended purposes. Furthermore, the mentioned above regulations only marginally address the technical specifications of bicycle lamps [32]. The requirements presented in Tables 1–7 do not, however, concern the significant structural technical aspects of bicycle lighting and the type and parameters of the light source used. In order to present this study on modern bicycle lamps, it is necessary to refer to the patent and bibliographic databases.

3. The Method

The database development method was implemented in accordance with the PRISMA 2020 system guidelines [33] (Figure 3) to develop the literature database that provides an overview of bicycle lamp designs and their smart and energy-efficient versions. The review methodology comprises the search query and databases and document selection criteria, which are in accordance with the recommendations indicated in the article [34]. Therefore, the PRISMA 2020 methodology was implemented to conduct the comprehensive literature review.

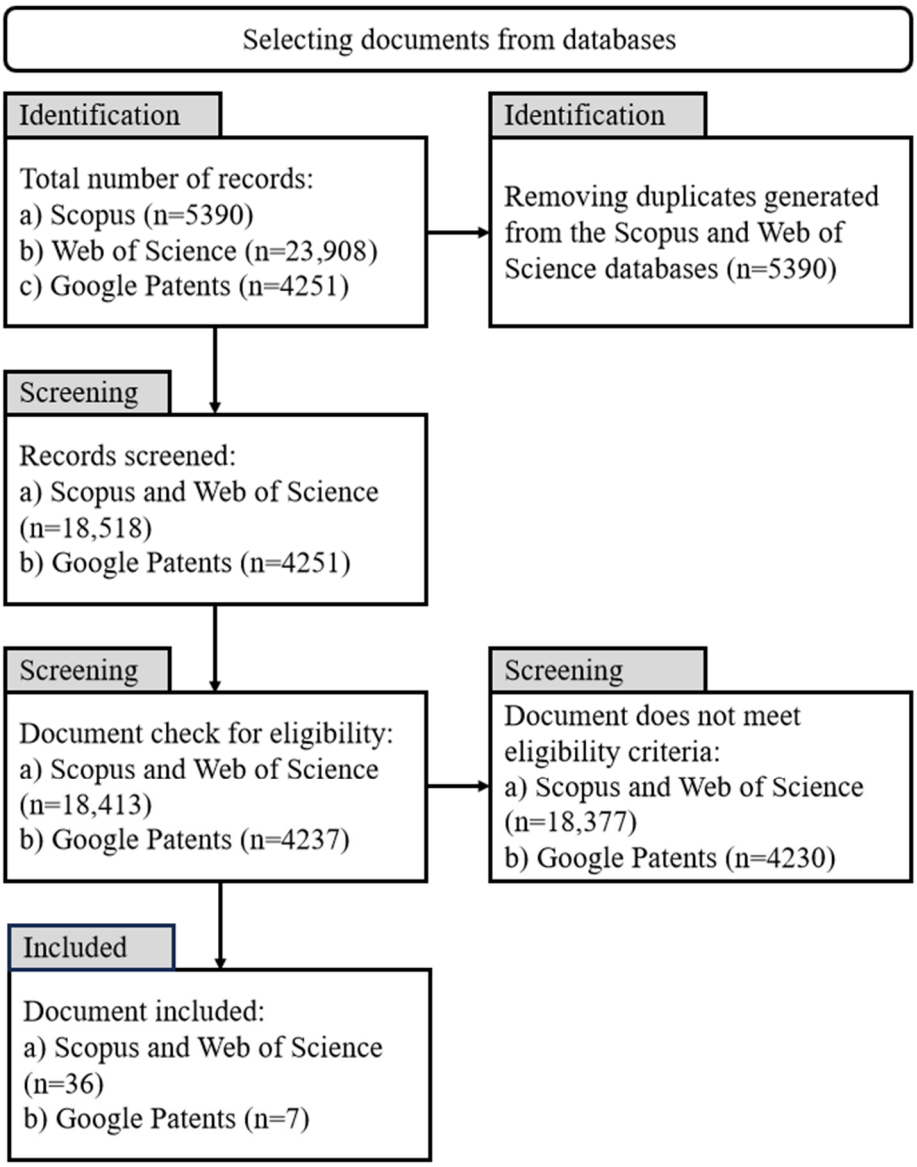


Figure 3. The diagram of the PRISMA 2020 system was utilized to develop the compendium of literature that presents the historical development of bicycle lamp design, including their energy efficiency and other quality parameters.

3.1. The Search Query

It was necessary to establish a set of criteria for defining keywords in order to identify literature that corresponds to the topic. A total of 45 keywords were defined, with the aim of ensuring a comprehensive and accurate search. To avoid any potential loss of valuable records, the possibility of differences in the naming of bicycles in English and American English was carefully considered when defining the keywords. It might be helpful to note that the keywords consisted of two words. The first word meant "bicycle", while the second word described a detailed feature or parameter of the bicycle. A variety of potential word combinations were explored, with the aim of identifying the suitable descriptions for lighting solutions designed specifically for bicycles. A comprehensive search of all keywords in the databases under consideration was conducted. The search of the abstracts, titles, and keywords of scientific papers using a series of keyword phrases was conducted as well. The following set of keywords, was which we developed through the authors' research: "bicycle and equipment", "cycle and equipment", "bike and equipment", "bicycle and head lamp", "cycle and head lamp", "bike and head lamp", "bicycle and

headlamp", "cycle and headlamp", "bike and headlamp", "bicycle and lamp", "cycle and lamp", "bike and lamp", "bicycle and lighting", "cycle and lighting", "bike and lighting", "bicycle and illumination", "cycle and illumination", "bike and illumination", "bicycle and visibility", "cycle and visibility", "bike and visibility", "bicycle and night", "cycle and night", "bike and night", "bicycle and brightness", "cycle and brightness", "bike and brightness", "bicycle and smart equipment", "cycle and smart equipment", "bike and smart equipment", "bicycle and smart lamp", "cycle and smart lamp", "bike and smart lamp", "bicycle and energy efficient equipment", "cycle and energy efficient equipment", "bike and energy efficient equipment", "bicycle and energy efficient lamp", "cycle and energy efficient lamp", "bike and energy efficient lamp", "bicycle and smart head lamp", "cycle and smart head lamp", "bike and smart head lamp", "bicycle and energy efficient head lamp", "cycle and energy efficient head lamp", "bike and energy efficient head lamp".

3.2. The Database and Documents Selection Criteria

In the course of the literature review, two databases containing scientific papers were utilized. Scopus and Web of Science are the selected databases. Scopus indexes over 3600 international technical journals from 1949 to present, while Web of Science includes the Science Citation Index, the Arts and Humanities Citation Index, and the Social Sciences Citation Index from 1989 to the present. The mentioned above databases were identified in the literature as the most comprehensive of all known databases [35,36]. Additionally, the Google Patents database was consulted. This database encompasses 12,476,504 full-text patents from 1790 to the present and the complete text of 7,082,473 patent applications from 2001 onwards. The scientific papers selected for incorporation into the database were evaluated according to the following criteria:

- this study included only patents and scientific papers, which were defined as scientific articles, conference papers, books, and technical reports,
- patents and scientific papers in multiple languages were included provided that they had an official abstract in English,
- the patents and scientific papers included in this study were obtained from the library, scientific databases, or the authors of the texts themselves,
- the patents and scientific papers that made reference to the design of modern bicycle lamps that could be classified as "smart",
- the patents and scientific papers that referenced the design of "energy-efficient" modern bicycle lamps,
- the patents and scientific papers related only to lighting for traditional bicycles,
- no temporal framework was established for the published patents and scientific papers, with the objective of illustrating the evolution of bicycle lighting technology over time.

4. The Results of the Review

The bibliographic descriptions of the retrieved publications were examined (following the PRISMA 2020 (Figure 3) scheme), and any instances of duplicate text were identified and removed. The database of literature on "Energy-Efficient and Smart Bicycle Lamps" developed in this manner was implemented in the SciSpace Literature Review software. This software allows for a comprehensive and optimal review of the literature [37]. In particular, these papers that met the description of bicycle lamp technical parameters were looked for. Those papers considered potentially relevant were collected, and the full text versions were then further reviewed for relevance. Similarly, the patents focusing on the technical details of bicycle lamps were reviewed.

A total of 5390 scientific papers were retrieved from the Scopus database, while 18,518 papers were retrieved from the Web of Science, resulting in a total of 23,908 papers. After the removal of duplicates and papers that were excluded due to a lack of relevance to the subject matter under analysis, the final database of scientific papers included in the article consisted of 36 papers. The analysis of patents yielded 4251 results; however,

after the removal of these papers, indicating a lack of relevance to the subject matter under analysis, the final database of patents included in the article consisted of 7 papers.

4.1. Lighting Fixture Design

Regardless of the technology, light sources emit light in any direction around them. Global trends make unlimited emissions unacceptable. This is attributable to the fact that global trends are aimed at the reduction of electricity consumption, light pollution, and negative impacts on the users. It is required to shape the photometric solid in order to adapt it to the specifications of the intended application. A photometric solid can be formed by a lighting fixture. Currently, the freeform method is used in the design of optical systems. In this method, the apparent surface area $S'(C, \gamma)$ of an optical system (with reflectance ρ) is shaped based on a specified direction (C, γ). For a light source with a luminance of L_S, this results in an assumed luminosity I in that direction (C, γ), as described by formula (1).

$$I(C, \gamma) = \rho \cdot L_S \, S'(C, \gamma) \quad (1)$$

The lighting fixture controls the light emitted by a source located within it [38–40]. This is achieved through the use of optical and mechanical components. These elements facilitate the direction, filtering, and transformation of the light emitted by the light source [38–40]. The components of a lighting fixture include diffusers, which disperse light in a uniform manner; reflectors, which direct beams into a designated area; lenses, which focus or disperse light; and filters, which modify color or eliminate harmful UV radiation. In the process of designing a photometric solid for a lighting fixture, it is important to select the optimal material, the geometry of the fixture, and the type and position of the optical system elements [38–40]. It is essential for designers to include all these aspects in the design of a lighting fixture. Subsequently, the designs are subjected to the mathematical simulations using dedicated programs (TracePro by Lambda Research Corporation, Westford, MA, USA, Photopia by LTI Optics, Westminster, CO, USA, Ansys Speos by Ansys, Canonsburg, PA, USA) [41,42]. If the required photometric solid is not obtained, design modifications and subsequent resimulations are required.

It is necessary that the lighting fixtures are in compliance with the standard requirements [43,44]. A comprehensive test to determine the photobiological safety of each lighting fixture is essential. The standard determines that a lighting fixture emits light harmful to the user. It introduces four hazards groups, and each of them defines the impact on human health. This is particularly important in the case of lighting fixtures equipped with LED sources where the excitation of the phosphor is obtained by a UV diode. The effect of the standard was to exclude the lighting fixtures equipped with radiation sources that could potentially cause negative effects for the human eye and skin.

4.2. The Influence of Light Sources on the Advancement of Bicycle Lighting Technology

The history of bicycle lighting demonstrates that it developed along with other lighting technologies, and particularly in response to the advancements in light sources and the development of automobile lighting. The earliest designs of bicycle lamps emerged in the second half of the 19th century and were based on oil (kerosene), gas, and acetylene [45–48]. The typical oil lamp design emitted a luminous flux of between 1 lm and 5 lm, depending on the specific type of oil and the configuration of the lamp [48]. In the course of operation, the efficiency of the lighting fixture decreased due to the dirtiness of the mirror system and the lampshade. Typically, this type of lamp could operate for several hours. During its operation, the wick wore out and the kerosene tank had to be refilled.

In the 1870s, gas lamps were introduced to the market, in which the light source was a flame created by burning gas (for example, using charcoal). These designs offered enhanced light efficiency; however, they were not widely accepted due to the challenges associated with their daily use [46].

The next stage in enhancing the light efficiency of bicycle lamps was the introduction of acetylene lamps. They were first used in the 1880s. The lamps operated by burning

acetylene, which was created by the reaction of calcium carbide with water [47]. Acetylene lamps were among the most light-efficient bicycle lamps in the 19th century and early 20th century. They generated a luminous flux of 15 lm to 50 lm [48]. The level of flux depended on the amount of acetylene produced and the design of the lamp. The lamp flame was bright and stable. The design of the optical system was similar to that described earlier and used in oil lamps.

The invention and use of light bulbs marked a turning point in the development of bicycle lamps. They made it possible to improve light efficiency and, as a result, cyclists' safety. At the same time, the improvement of light efficiency in bulbs and optical systems influenced the constant improvement of the energy efficiency of bicycle lamps.

The first bulb bicycle lamps were created in the early 1900s, right after cars started using lighting. The first designs used carbon filament bulbs, then tantalum, and later tungsten. They were powered by very primitive batteries. These designs only lasted a short time because the carbon filaments did not last long, and the batteries or cells did not hold a charge very long. The big breakthrough came in the early 1920s when bulb bicycle lamps were introduced and powered by lead-acid batteries or better-quality cells.

Bicycle lamps made in the early 1900s are considered to have the power of 2W to 5W and a luminous efficiency of about 3 to 5 lm/W This meant they could emit a luminous flux of 10–25 lm. It is also worth noting that carbon filament bulbs were not very resistant to large shocks.

Then, tantalum filament bulbs (also known as Tantalum Filament Bulbs) started being used in bicycle lighting. These bulbs were similar in power to carbon bulbs but had a luminous efficiency of about 6 to 10 lm/W. This meant that the luminous flux of tantalum bicycle bulbs ranged from about 18 lm to about 90 lm. Tantalum bulbs were more efficient and lasted longer than carbon bulbs. This means that acetylene lamps often produced a greater amount of light at that time [46]. In the early 1900s, tungsten filament bulbs were introduced to bicycle lamps. Tungsten has a much higher melting point than tantalum and carbon, which meant that bulbs could be made much more efficiently and therefore used less energy. Tungsten bulbs are considered to be about 8 to 15 lm/W efficient. Therefore, they could produce a luminous flux of 16 lm to 90 lm with a typical power of 2 W to 6 W. The next step in making bulbs more energy efficient was to fill them with gases like argon or nitrogen. This boosted light efficiency and increased the emitted flux by up to 100 lm. The durability of the bulbs was also extended, and they demonstrated enhanced resistance to shocks. The observed durability of carbon bulbs was approximately 500 h, tantalum bulbs achieved a durability of approximately 1500 h, and tungsten bulbs demonstrated a durability of approximately 2000 h.

In the subsequent decades of the 20th century, the widespread use of light bulbs facilitated their considerable development, which in turn enabled a substantial enhancement in the energy efficiency of bicycle lighting.

The introduction of halogen bulbs was a significant advancement in the energy efficiency of bicycle lighting. The use of halogen bulbs in bicycle lighting started in the 1970s and 1980s. The implementation of halogen gas (bromine or iodine) within the bulb and the elevation in bulb temperature resulted in enhanced lighting parameters and durability. This enabled the implementation of the halogen cycle, which reduced tungsten evaporation and its deposition on the bulb. Halogen bulbs had the power of 10 W to 20 W and a luminous efficacy of 15 lm/W to 25 lm/W. As a result, the maximum flux of a halogen bulb utilized in bicycle lamps could reach up to 500 lm.

A further significant advancement in the field of bicycle lighting was the introduction of light-emitting diodes (LEDs). The use of light-emitting diodes (LEDs) in bicycle lamps began in the 1970s and 1980s. Given the low luminous flux of the initial LEDs and the straightforward production of colored LEDs, they were predominantly utilized during this period as the rear position lights. The power output of these devices was relatively low, ranging from 0.1 W to 0.5 W, while their luminous efficiency was between 1 lm/W and 5 lm/W. In the final decades of the 20th century and the initial decades of

the 21st century, LED technology underwent further advancement [49,50]. Therefore, they were subsequently implemented as the principal source of illumination for bicycles. The power of the LEDs utilized ranged from approximately 1 W to approximately 3 W, while the luminous efficiency increased from approximately 10 lm/W to approximately 20 lm/W. However, halogen lamps enabled the generation of a greater luminous flux from the lamp. Subsequently, single LEDs were integrated into LED matrices, thereby enabling the generation of higher light fluxes in bicycle lamps. A significant benefit of LED-based lighting compared to traditional incandescent bulbs is their markedly enhanced durability, with the operational lifespan ranging from a dozen to several dozen thousand hours. LED's insensitivity to shocks as well as their relatively straightforward control of the LED light level are their additional advantages.

At the beginning of the 21st century there was a further enhancement in the efficiency parameters of LEDs. The power output of individual LEDs increased to approximately 5 W with a luminous efficacy of 60 lm/W. This enabled the generation of a luminous flux of up to approximately 300 lm.

In the second decade of the 21st century, there was a further improvement in the energy efficiency of bicycle lamps using light-emitting diodes. In this case, the power output of the individual LEDs increased from approximately 5 W to approximately 10 W, with a resulting luminous efficacy of 100 lm/W. This enabled the LEDs to generate a maximum luminous flux of 1000 lm. However, manufacturers often utilize multiple LEDs of reduced power to achieve higher luminous flux values. The shape of the current generation of bicycle lamps often resembles the one of the classic flashlights made of LEDs, which can exceed 150 lm/W with beam intensities exceeding 2000 lm.

4.3. The Optical System of Optical Lamps

The improvement of energy efficiency and luminous efficacy of bicycle lighting has also been influenced by advancements in the design of bicycle lamps' optical systems. The optical system is used to shape the luminous flux emitted from the light source in a manner that optimizes the intended lighting effect while minimizing losses in the luminous flux of the light source. The development of light sources has resulted in corresponding changes to the optical systems used. From the initial designs of bicycle lamps, the implementation of basic optical systems has enhanced the luminous efficiency of a given lamp. The earliest designs of bicycle lamps were based on oil (kerosene) lamps and emerged on the market in the 1860s. In the 1880s, the bicycle frame by Lucas (England) was introduced to the market. The company still operates on the market, although its current focus is on the production of light sources. The operational principle of this type of lamp (Figure 4) was based on the combustion of oil (typically kerosene) through the lamp wick. The optical system consisted of a flat, round mirror (typically crafted from polished metal such as copper or brass) that was designed to reflect the lamp's flame in a directional manner. In some solutions, an additional lens was positioned at the front of the apparatus, serving to magnify the flame. The flame of such a lamp was susceptible to fluctuations in atmospheric conditions, resulting in an unstable shape and dimensions. The optical system construction of this lamp enabled the amplification of the light emitted from the flame. It is estimated that the optical system amplification reached the level of approximately 1.5. These lamps had a relatively low luminous efficacy [48].

The significant advancements in the construction of optical systems for bicycle lamps occurred at the end of the 19th century and the beginning of the 20th century. At that time, bicycle lamps began to use bulbs that had a compact and relatively small filament with a constant luminous surface area. This innovation enabled the light beam to be shaped more effectively than in oil lamps. In the 1920s and 1930s, simple metal reflectors with a concave shape started being used. Metal reflectors had a reflectivity of around 0.5. By the 1930s, reflectors were already being painted silver. In the 1950s, the reflectors were being chrome-plated on a larger scale. In the 1950s and 1960s, plastics like acrylic and polycarbonate started being used to make reflectors. This enabled us to make reflectors as

well as lenses of more and more complex shapes. The coated and chrome-plated reflectors could have reflectivity of 0.8 to 0.9. At the beginning of the 20th century, the reflection coefficients of such reflectors exceeded 0.95 thanks to the improvement of the technology of applying reflective materials to reflectors and to the complex composition of the applied reflective layers (containing, among others, silver). The development of the reflector design and the coating method influenced the further improvement of the light efficiency and energy efficiency of the entire lighting system of bicycle lamps. Towards the end of the 20th century, as the result of using LEDs in bicycle lamps, there was the further development of optical systems. At that time, the lenses to shape the LED light beam started to be used on a larger scale. In the early 2000s, collimators began to be used in LED optical systems [51]. Collimators had even better system efficiency thanks to the used materials and the total internal reflection of light, as well as the ease and precision of the shape. Collimators were most often made of polycarbonate and optical glass. The optical efficiency of collimators reaches 90%. Typical designs of optical systems for bicycle lamps will be discussed later in the work.

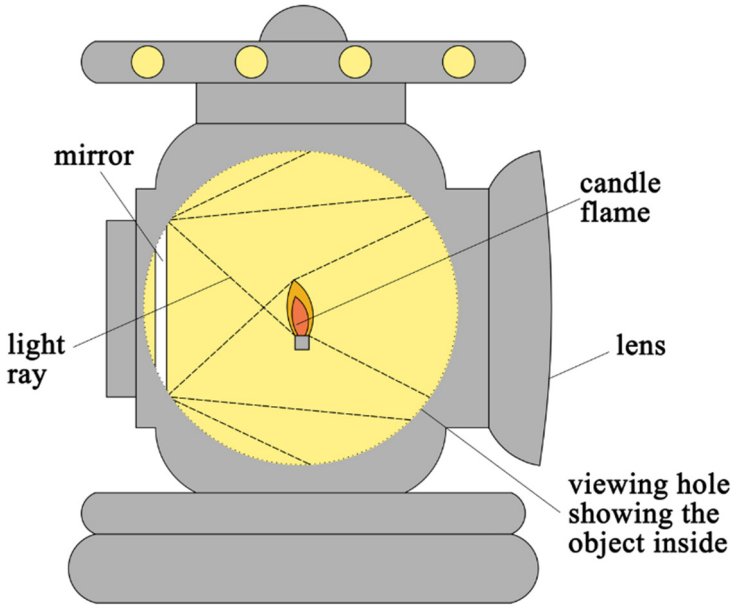


Figure 4. The oil-based bicycle lamp diagram.

Over the next few decades, paraboloidal mirror systems (see Figure 5) started being used in optical system designs. The bulbs were powered by batteries or generators. The batteries needed to be replaced every few dozen hours, and the bulbs lasted several dozen or several hundred hours. Sometimes reflector systems were paired with the external Fresnel lenses, which helped shape the photometric solid even more. The vast majority of such optical system designs were mainly focused on achieving a high gain for the optical system. The photometric luminous curve of these lamps evinced rotational symmetry. However, a notable drawback was observed in the form of a lack of uniformity of the light spot.

The structures using free-form reflectors (FFR) [52] were the next stage in the development of bicycle frames [52]. In these designs, the reflector was divided into numerous independent zones where each zone could be a parabolic reflector with a different focal length and distinct dimensions and could perform different lighting tasks. The reflector fragments were designed in such a way that despite differences in optical parameters (differences in shape), they were able to create the most uniform surface possible and mutually complement the photometric solid. As a result of this design, it was possible to shape the photometric solid of the front bicycle lighting fixture in a highly advanced manner. This resulted in a notable enhancement in the uniformity of illumination in the

frontal area of the bicycle. This methodology made it possible to meet the illumination requirements stipulated in the German standard [29].

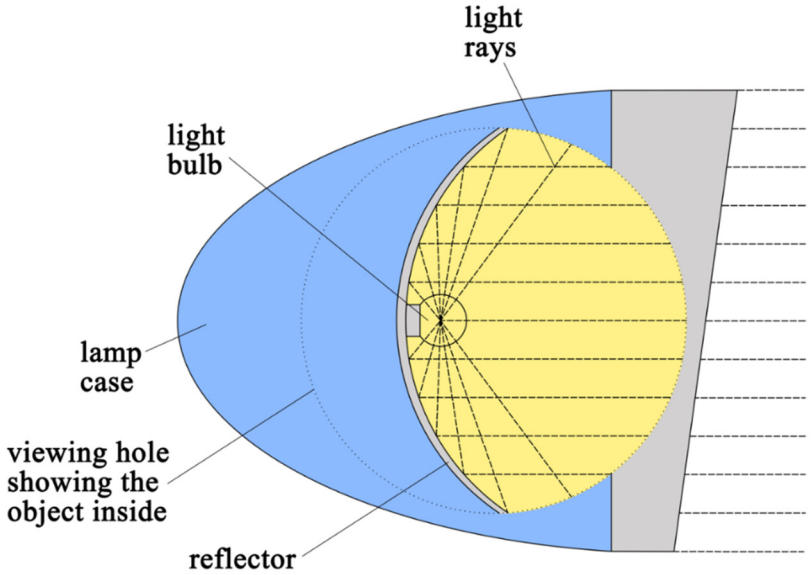


Figure 5. The diagram of the optical system (mirror reflector) of a bicycle lamp built using a light bulb.

The next phase of advancement in bicycle lamp design involved using the electroluminescent diodes in their construction. Using the light-emitting diodes (LEDs) in the design of optical systems contributed to the improvement of the lighting parameters of bicycle lamps. On the one hand, LEDs typically emit light into a single half-space, facilitating the shaping of the light beam. On the other hand, the possibility to shape the lenses in a precise way enhanced the efficacy of bicycle frame lighting. Additionally, the durability of LEDs in bicycle lighting is much bigger compared to bulbs, and the resistance to shocks of LEDs is also considerably higher than that of bulbs. In the early stages of development, LEDs replaced traditional incandescent bulbs in optical systems that were based on parabolic reflectors. The photometric solid was most often rotationally symmetric. The Fresnel lens [53] was often added to the classic optical systems in order to enhance the uniformity of illumination. In more sophisticated designs, FFR reflectors were used [54]. The implementation of the FFR solution [55] led to a discernible enhancement in the uniformity of the horizontal stretching of the light spot, utilizing a 1 W LED source and a multitude of reflector segments, which formed a kind of optical fiber.

The advancement of lighting fixtures with semiconductor sources resulted in the incorporation of a phosphor-converted white LED light source and a reflector comprising eight segments. The four lower segments of the reflector provided a sharp cut-off line edge for the emitted light beam [56], ensuring that other road users are safeguarded from the glare emitted by the light source. In the process of designing the reflector structures of lighting fixtures, the non-imaging optics theory and Snell's law [57] were also used as the basis for the theoretical framework. In general, the objective is to achieve high gain and glare reduction [58].

However, in the design of bicycle lamps, there was a considerable shift in focus towards the essential parameter, which is a high degree of uniformity in the illumination of the road ahead of the cyclist while achieving lighting standards. The classic solutions, which were rotationally symmetrical photometric solids, were primarily concerned with obtaining a long range of front lighting lamps. However, in order to ensure uniform illumination of the area in front of the bicycle, it was necessary to utilize bicycle lighting fixtures with the asymmetrical photometric solid.

The following phase in the development of bicycle lighting fixtures involved the substitution of traditional reflectors with solid collimators (Figure 6) or the integration of reflector and lens systems [59].

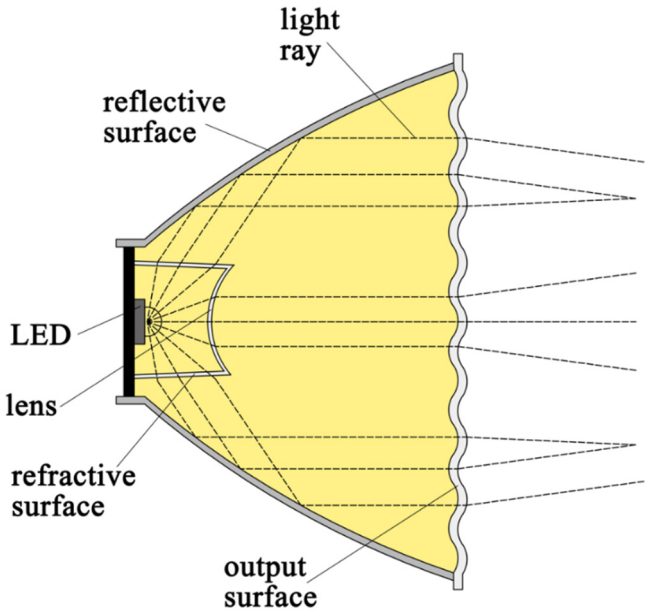


Figure 6. The diagram of the optical system of a bicycle lamp using a collimator and LED.

The operation of collimator systems is based on the phenomenon of total internal reflection, which results in minimal luminous flux losses. Furthermore, collimators allow the precise shaping of the photometric solid of a bicycle lamp. The optical systems with collimators can achieve optical efficiency above 90%.

4.4. Modern Complex Optics and Other Innovative Design Solutions

In addition to the typical designs of optical systems for bicycle lamps, there are systems that represent a combination or extension of the mentioned above optical systems. One of the designs described in the patent [60] involved the use of an RGB LED as the light source. In order to obtain a uniform light color, the optical fiber was used, in which the individual basic colors were combined. Next, the optical fiber output was positioned at the focal point of the lens, which allowed it to form a photometric solid. This solution allowed the selection of an appropriate light color and the precise formation of the photometric solid of the bicycle lamp. However, this particular solution is characterized by a relatively low level of energy efficiency.

The optical system made up of a lot of bifocal reflectors (or two single-focus reflectors placed appropriately among each other) is another modern, complex type of bicycle lamp design [61]. The LED light source is placed in one focus, and the light flux is directed from there to the second focus of the lighting system. The second focus is placed in the optical fiber, which can collect and mix light from several optical systems and then send it to any place (thanks to the optical fiber). The optical fiber collecting light from the second optical system can be inserted into a larger optical fiber, which collects light from several smaller optical fibers (collecting light from several optical systems). The light can be directed to any place by means of the optical fiber. This type of lighting system is also characterized by a relatively low level of energy efficiency.

In the next solution of the optical system, an idea was proposed for a multi-source LED lamp (reflector) [62]. In practice, due to the low power of individual LEDs, it is necessary to utilize many LED sources positioned close to one another. As the configuration of the LEDs becomes denser, a considerable proportion of the luminous flux emitted from the lateral surfaces of individual LEDs is lost. In this solution, a multi-curve collimator is used to

collect the luminous flux emitted from the side surfaces of the LEDs in an optimal manner. This solution enables the effective utilization of the luminous flux with a high degree of LED packing, particularly for low-power LEDs. This type of optical system ensures high energy efficiency.

In addition to the just-discussed lighting solutions, there are also those that complement classic bicycle lighting with the strategic placement of LED sources, for example, on the bicycle frame [63]. Similarly to automotive lighting, such a configuration of light sources provides contour lighting, which is defined as lighting that illuminates the shape or outline of an object. This solution significantly improves the visibility of the bicycle at night. This configuration ensures that the bicycle's visibility does not depend on the operation of the primary lighting fixture. It needs to be highlighted that when these solutions are implemented, it is of key importance to ensure the appropriate selection of luminance for the individual LEDs (acting as contour lights). The inappropriate luminance level (one that is excessively high) may result in glare for other road users at night. A comparable approach is the proposal of distributing light along the bicycle frame via a semi-transparent tube [64]. Consequently, the visibility of the bicycle was improved. Moreover, such solutions using light bulbs (concerning contour bicycle lighting) were previously implemented in the 20th century. One such solution is the concept of placing light bulbs on the spokes of a bicycle [65]. At present, the bulbs that were previously used in such solutions have been replaced by light-emitting diodes (LEDs). Through the implementation of dedicated control systems, the LED light can be adjusted to match the rotational speed of the wheel, thereby enabling the display of diverse patterns on the spokes (so-called programmable LED lighting on bicycle wheels). Additionally, in the 20th century, the conventional lighting solutions were supplemented with the direction indicators [66]. This innovation significantly facilitated navigation for cyclists, eliminating the necessity to indicate direction of movement by hand. Nevertheless, this solution did not gain widespread support.

According to the declarations of well-established manufacturers with several decades of experience on the market, the latest designs of mass-produced bicycle lights have been found to achieve lighting fixture flux values of up to 1000 lm, 2000 lm, and even above 4000 lm. It is of key importance to accurately identify the light-shadow boundary in order to improve the safety of all public road users. It is worth mentioning that the luminous flux is comparable to that of automobile projectors. The luminous flux of a bicycle lamp (or the light source used in it) and the scope of illumination are also not subject to any formal limitations. This is particularly evident in countries where there is a lack of standardization in this area, with the exception of the German standard, which does impose certain limitations. The focus is just on the practical utility of the lighting, which should be sufficient to meet the user's needs while avoiding glare or disorientation of other road users. In this case, the method to examine the impact of additional features of bicycle lights on the perception, behavior, and acceptance of users [67] is quite important.

It is significant that the device is capable of regulating the luminous flux, which is essential for accommodating the varying lighting conditions that may be encountered during the ride. Such circumstances include instances where the device is used close to road lighting, in open spaces without buildings, or in the cloudy weather. Furthermore, the ability to alter the luminous flux can contribute to energy savings by reducing power consumption. It is necessary that this lamp is capable of operating as long as it is possible. The battery power should be sufficient to enable the illumination of the full beam for a period of several hours, depending on the ambient temperature. In this regard, the use of high-performance light-emitting diodes has proved to be advantageous. The possibility of using a flashing mode is another significant consideration. The flashing mode improves the visibility of the user in conditions of heavy traffic during the day and after dark. The pulsating light highlights the presence of the not typical road user in a distinctive manner, thus enabling them to be noticed quite early and facilitating an appropriate response [68]. It is important to note that observers did not perceive the flashing light as irritating when observed from a greater distance [67]. However, the light was perceived as irritating and

causing glare [67] when observed from a closer distance. It is necessary to restrict the luminous flux emitted by lamps equipped with high-power diodes in flashing mode, as it is crucial to avoid the disorientation of other road users [69].

4.5. Smart Bicycle Lighting

The introduction of electroluminescent diodes in bicycle lighting led to the emergence of straightforward smart solutions in the second half of the 20th century. The possibility of reducing the luminous flux emitted by bicycle lamps is the simplest smart solution. The reduction is typically initiated by the main power button. In the 21st century, smart solutions have become more advanced. The review of the LED lamps currently available on the market has revealed several worth mentioning solutions.

In particular, the special remote control placed on the handlebar is an extension of the ability to adjust the luminous flux to prevailing conditions. This remote control is capable of modifying the level of luminous flux and activating or deactivating the LED lamp, thereby enabling the users to adapt the lighting to suit their needs. The remote control and the bicycle lamp are in communication with one another via the Bluetooth interface, which allows for the transfer of data between the two devices. Furthermore, these lamps can be operated by a dedicated mobile application. It is worth highlighting that the majority of well-known bicycle lamp manufacturers currently offer such solutions.

Selected bicycle lamp models are equipped with displays that provide users with information regarding the operational status of the lamp, thus facilitating a comprehensive understanding of the device's functionality. Thanks to these devices, the user is able to obtain information regarding the operational status of the lamp, including the remaining operational time, the percentage of battery charge, and the current time. The sophistication of the display varies according to the specific lamp model and the manufacturer. In the case of simpler solutions, a status strip is the only indicator, and this strip displays the number of lit mini diodes to indicate the battery charge level. Additionally, there are lamps that have both solutions, namely a display and an LED strip.

The smart solution proposed by British Ultimate Sports Engineering Ltd. (Pulborough, UK) is worth discussing. The implemented Smart system automatically adjusts the light to provide the increased power during periods of rapid acceleration and then dims it on slower sections. The system obtains data from digital 3D accelerometers, including a gyroscope, which enables it to adapt the lighting to adjust to the driving conditions.

There are also solutions on the market where bicycle lights have a mode in which they switch to daytime lights. This solution improves the visibility of cyclists on the road, even during the day. This is of particular significance in the context of Switzerland, where since April 2022, daytime lights have become mandatory for electric bicycles.

An even more advanced solution, which has previously been implemented in motor vehicle lighting, is the capacity to alternate between the running, dipped, and main beam lights. In more advanced solutions, this process is automated. The sensor is capable of identifying the prevailing ambient conditions and subsequently regulating the lamp's operating mode in accordance with these observations.

The objective of introducing these smart solutions is to improve the comfort and security of cyclists while reducing the amount of the required equipment. The modifications to lighting fixtures are a prevalent trend. They have been equipped with new smart solutions in addition to their fundamental purpose of illumination. In their study [11], the authors utilized intelligent bicycle lights equipped with a vibration measurement system. Thanks to using the vibration measurement system, it was possible to assess the user's comfort and safety with the creation of a map of bicycle routes and a description of their condition, classified as either smooth or extremely bumpy. The lighting can be adapted to suit the characteristics of the given route. Another strategy to enhance the safety and comfort of the cyclist was the implementation of the BLCS (Bicycle Light Communication System) [70], which enables the cyclist to communicate with their surroundings through

signaling their intention to brake, make a turn, and even indicating the speed of their moving bicycle based on a modified bicycle lamp.

The increased functionality of bicycle lighting is associated with the increased demand for electricity. This energy should come from a stable and reliable source that does not require frequent changes or the user's intervention. Such a solution is the implementation of a smart, environmentally friendly power system that eliminates the necessity for battery replacement or recharging [71]. The electric energy is obtained from the vibrations of the bicycle frame caused by rolling, where mechanical energy is converted into electrical energy [71]. Additionally, the authors of the publication entitled Voltage Improvement of a Swing-Magnet-Type Generator for Harvesting Bicycle Vibrations emphasized the significance of recovering electrical energy from vibrations. They proposed a swing-magnet-type generator, which yielded a voltage sufficient to power an electroluminescent diode [72].

In addition to the requirements for traditional lighting fixtures, modern smart lighting solutions are designed to automatically adapt to current road conditions in order to enhance safety and improve user comfort. This is accomplished through the implementation of the sophisticated sensors and algorithms that monitor and adjust the lighting in accordance with the alterations in the surrounding environment [73,74]. By monitoring road conditions (e.g., road surface quality, collisions, traffic intensity) or prevailing weather conditions (e.g., snow, rain, fog), smart lighting fixtures should adjust their lighting in real time to optimize visibility in challenging road conditions and alert the user to potential hazards. The intelligent fixture is the future of bicycle lighting. Currently, research is being conducted on technological solutions and control algorithms. Nevertheless, this does not prevent the utilization of solutions that are currently accepted by society. It is possible to use a presence sensor (to enhance the detection of pedestrians or vehicles), a light sensor (to adjust the lighting fixture to natural light conditions), a weather sensor (to adapt the lighting to weather conditions), a traffic sensor (to choose safe bicycle routes in real time), or image processing systems (to dynamically adapt the lighting to road or weather conditions). In the context of data analysis, predictive algorithms represent the optimal and most effective solution. These algorithms are capable of adapting to environmental conditions based on the reference data and measured data, thus offering a potential solution to the challenges posed by changing conditions.

A variety of techniques may be utilized for the transfer of data between the central unit and the sensors. One solution that is widely utilized is a cable connection, which ensures minimal energy consumption and stable, rapid data transmission. However, the wires may ruin the look of the bike. It also might not always be possible to extend the wire to the sensor. Bluetooth systems are also a popular choice due to their ability to facilitate connections between sensors and numerous receivers with minimal energy consumption. However, this technology is constrained by the limitations in terms of range and the potential for interference in the highly urbanized areas. Furthermore, there are techniques for the transfer of extensive data sets via Wi-Fi. However, this approach is very costly and necessitates a significant increased use of energy. A more detailed description of the indicated technologies can be found in the referenced articles [75–78].

4.6. The Potential of Further Bicycle Lamps Development

The review of the potential for further development of bicycle lamps indicates that there is a strong possibility of further adoption of solutions from automotive lighting technology. Within the next couple of years, LED Matrix [79] and a special control system that allows vehicles to operate with high beams on at all times may also be used in bicycle lighting. The presence of other road users is identified, and the areas in which they are situated are less illuminated. Consequently, the entire road is illuminated with the full luminous flux of the automobile headlight, while only those areas in which other road users are located are darkened. This system requires the integration of a camera with the ability to monitor the surrounding environment. At the present time, this appears to be a remote

possibility. It is often observed that sophisticated solutions gain popularity at a remarkable pace, particularly in relation to improving the safety of cyclists and other road users. In the future, bicycle lamps can be equipped with sensors that will adjust the level of lighting to the conditions on the road. Furthermore, the integration of energy-efficient LED matrix technology into bicycle lighting systems will undoubtedly facilitate the advancement of intelligent lighting solutions. A promising avenue for further research is the work previously outlined regarding bicycle marker lights, which markedly enhance visibility.

A promising area for further investigation is the development of systems that facilitate advanced communication between cyclists and their surrounding environment, based on a modified bicycle lamp. This includes the creation of systems that enable cyclists to signal their intention or to measure environmental parameters with the aim of informing the cyclist about potential dangers.

The system that uses the vibrations generated by the bicycle itself to charge the battery is another system with considerable potential for integration into a bicycle. This system prolongs the operational lifespan of bicycle lamps significantly, thereby increasing their utility.

5. Conclusions

The article provides an overview of the evolution of bicycle lighting fixtures from their initial designs to the contemporary models currently available in the 21st century.

The evolution of bicycle lamp design over time provides an example of significant technological advancement. The luminous flux of bicycle lamps has increased significantly over the past 150 years, from a mere few lm to over 4000 lm. Regardless of the stage of development of bicycle lamps, designers have consistently sought to improve road visibility and facilitate safe cycling at night. In the 21st century, there has been a sustained effort to improve the energy efficiency of bicycle lamps and integrate new smart functions.

The earliest designs were based on the technology of oil lamps, in which the flame was the light source. Even in these relatively simple solutions, optical systems such as a flat mirror or a simple lens were employed. The subsequent designs of bicycle lamps were influenced by the advancements in light source technology and the evolution of optical systems.

The introduction of light bulbs was the next milestone in the evolution of bicycle lamps. The enhancement of the luminous efficacy of the light source and the reduction of its dimensions facilitated a substantial improvement in the energy efficiency of bicycle lamps and the development of more sophisticated optical systems. In the subsequent period, the design and configuration of reflectors in bicycle lamps were optimized with the objective of concentrating the light beam and maximizing the range of bicycle lamps. These streps also contributed to the enhancement of the energy efficiency of the mentioned above bicycle lamps.

The introduction of electroluminescent diodes, which represented a significant improvement over previous lighting technologies, was the next key advancement in bicycle lamp technology. The advantages of LEDs were numerous, including high luminous efficiency, long durability, high luminance, and ease of control. Moreover, the integration of solid collimators into the design of contemporary signal lamps enabled a more effective shaping of the luminous flux, thereby enhancing energy efficiency. In light of these developments, designers of lighting fixtures began to prioritize two key objectives: firstly, to limit the potential for blinding other road users, and secondly, to improve the uniformity of illumination on the roadway illuminated by a bicycle lamp. These ideas facilitated further enhancements in cyclist safety in road traffic.

At the present time, consumers do not only look for lighting products that perform the necessary functions, but they also expect the products to be energy efficient. The review of the literature has revealed that lighting fixtures equipped with halogen sources have a luminous efficacy of 15 lm/W to 25 lm/W, while LED-based lighting fixtures have a

luminous efficacy of 150 lm/W. This affects the ability to generate much larger luminous fluxes at the same power. This has an impact on superior road illumination.

The review of the latest designs of bicycle lamps reveals that in addition to the long range of light beams, attention has been paid to ensuring uniform illumination of the road that is in front of the bicycle. This issue has been influenced by several factors, including the introduction of more rigorous standardization requirements in Germany, technological advancements in lamp design, and an increased awareness among users. Furthermore, designers now have the ability to shape the photometric solid of bicycle lamps through the use of advanced optical systems.

The principal advantage of LED lighting over traditional sources (incandescent or halogen) is its markedly superior durability. The product's lifespan can range from several to several hundreds of thousands of hours. This is a significant advantage of LED technology. Furthermore, LEDs are shock-resistant and can be readily adjusted to accommodate a variety of lighting requirements, which is a key feature of intelligent lighting systems.

The available research suggests that smart technology will become dominant in the coming years. However, based on the trends and technological solutions discussed in the article, it is possible to identify emerging features that will shape the future of smart lighting fixtures. The advancements in bicycle lamp design will be shaped by the increase in intelligent smart systems. It is anticipated that bicycle lamps will be capable of being controlled and adjusted in accordance with changing road conditions, particularly at night, with the objective of enhancing road safety. It is expected that bicycle lamp designs will be similar to those of automobile lighting, particularly in terms of functionality. The future of bicycle lighting will entail the integration of external sensors, thereby enabling a more efficient utilization of the luminous flux of light sources—a feature already observed in the most advanced designs. The intelligent lighting systems will be programmed to detect the dusk and subsequently activate the bicycle lighting. The range of bicycle lamps will be extended, and the uniformity of illumination on the road ahead of the bicycle will be enhanced. Furthermore, the potential for glare to other road users will be solved through the integration of light beam cutoff mechanisms in specific locations where such glare could pose a hazard. The above-mentioned smart bicycle lamp solutions are quite expensive and exceed the price of many bicycles. Nevertheless, the examination of the automotive market shows that similarly to bicycles, the most sophisticated lighting technologies were initially limited to the most expensive premium-class cars. However, as this technology became more widespread, the sophisticated lighting system solutions also began to be utilized in mid-range cars. It seems reasonable to suggest that intelligent and advanced energy-efficient lighting systems will become widely used in bicycle lighting in the near future.

Author Contributions: Conceptualization, I.F., M.L. and D.C.; methodology, I.F., M.L., J.F. and D.C.; writing—original draft preparation, I.F., M.L., J.F. and D.C.; writing—I.F., M.L., J.F. and D.C. All authors have read and agreed to the published version of the manuscript.

Funding: Electrical Power Engineering Institute, Warsaw University of Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to (privacy).

Acknowledgments: The author would like to express his gratitude to the Electrical Power Engineering Institute Warsaw University of Technology for funding and the possibility of publishing the results of the conducted research.

Conflicts of Interest: The authors declare no conflicts of interest.

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